Oak Ridge National Laboratory

Project ID: mat192

Fundamentals of Austenitic Alloy Via Additive Manufacturing (AM)*

*Subtask 3B1 under the Powertrain Materials Core Program (PMCP)

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Materials Science and Technology Division
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2020 DOE Vehicle Technologies Office Annual
Merit Review, June 4, 2020

Context overview: VTO Powertrain Materials Core Program

Timeline

- Lab Call Award: July 2018
- Program Start: Oct 2018
- Program End: Sept 2023
- 30% Complete

Budget

- $30M/5 years

Barriers to new alloys

- Higher power density, higher efficiency engines; resulting in increasingly extreme materials demands
- Cost of advanced engine materials
- Development time/cost of new materials
- Scaling new materials technologies to commercialization

FY20 Program Research Thrusts	FY20 Budget	Partners
Thrust 1. Cost Effective Lightweight High Temp Engine Alloys	$1.05M	ORNL
Thrust 2. Cost Effective Higher Temp Engine Alloys	$1.525M	ORNL, PNNL
Thrust 3. Additive Manufacturing of Powertrain Alloys	$1.075M	ORNL
Thrust 4A. Advanced Characterization (supporting Thrusts 1-3)	$1.025M	ORNL, PNNL, ANL
Thrust 4B. Advanced Computation (supporting Thrusts 1-3)	$0.6M	ORNL
Thrust 5. Exploratory Research: Emerging Technologies	$0.75M	ORNL, PNNL, ANL

Overview: Subtask 3B1 - Fundamentals of Austenitic Alloys Via Additive Manufacturing (AM)

Timeline

- Project start: Oct 2018
- Project end: Sep 2023
- Percent complete: 30%

Barriers to AM of Austenitic Alloys

- Very few austenitic steels ready for AM
- No high temperature data for austenitic steel
- Cost and scaling barriers for AM
- Development time

Partners	FY20 Budget
Subtask3B1: Fundamentals of Austenitic Alloy Via Additive Manufacturing	**$200k**
Thrust 4A: Advanced Characterization	**$30k**
Thrust 4B: Advanced Computation	**$27k (FY19)**

Relevance:

- AM allows for advanced design creating opportunities to improve component performance
- Significant gap of knowledge
  - Specific thermal history
  - Very fast cooling → unique microstructure, properties
  - New alloys needed

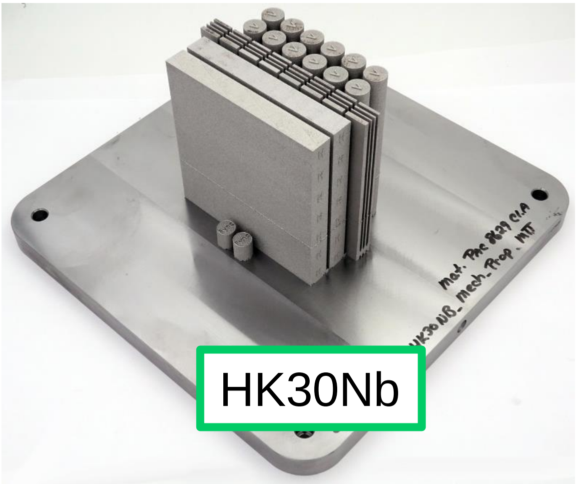
Exhaust manifold

Property	Cast HK30Nb	AM 316L	AM HK30Nb
Microstructure	Segregation, Carbides	Cellular structure, Twinning	Cellular structure, Twinning, Carbides
Yield St. 700°C	135 MPa	237 MPa	470 MPa
Creep 700°C	150MPa, 120h	Low	150MPa, 310h
Fatigue 800°C	0.5% strain, R=-1 1650 cycles	?	?

FY20 Milestones

- Q1. **Fabricate austenitic stainless steels** by powder bed fusion (PBF) and binder jetting with high C content for operating temperature >650°C. **COMPLETE**

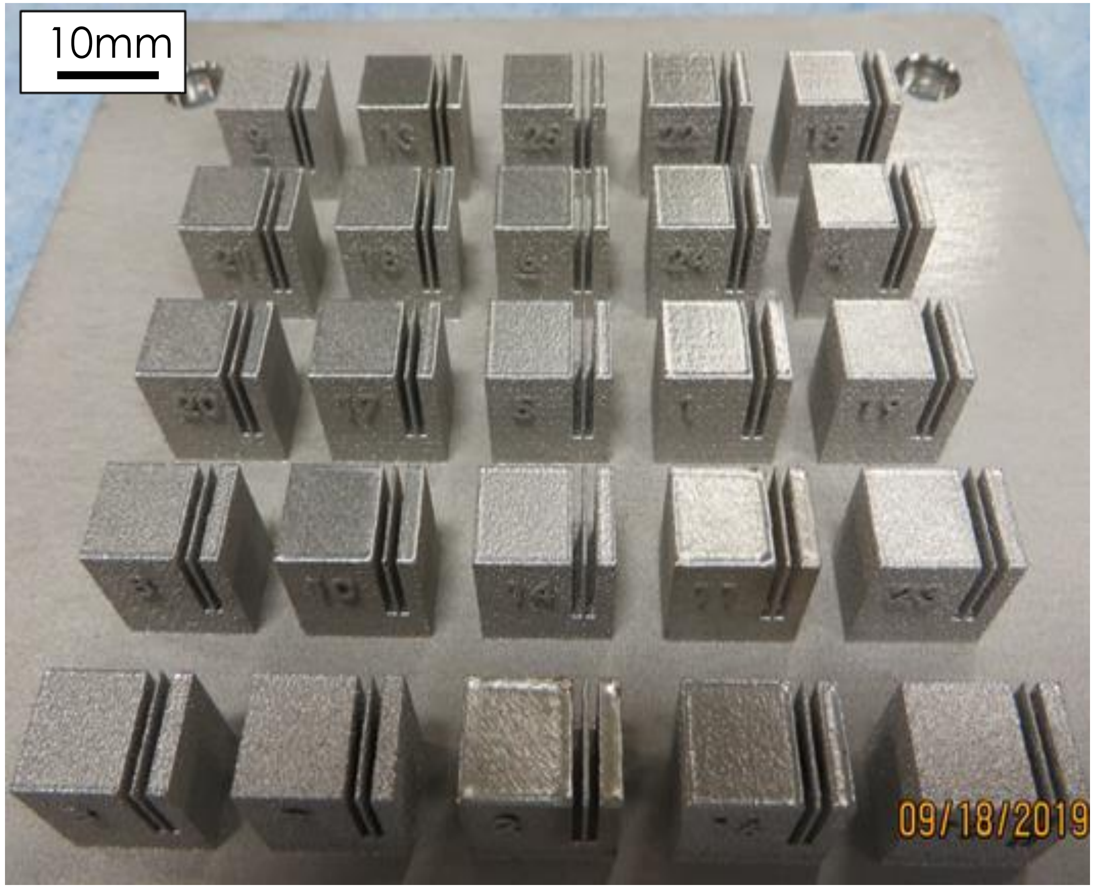
- Q4. **Submit manuscript** comparing the high temperature tensile and oxidation behaviors of austenitic steels fabricated by AM and conventional processing routes. **On target**



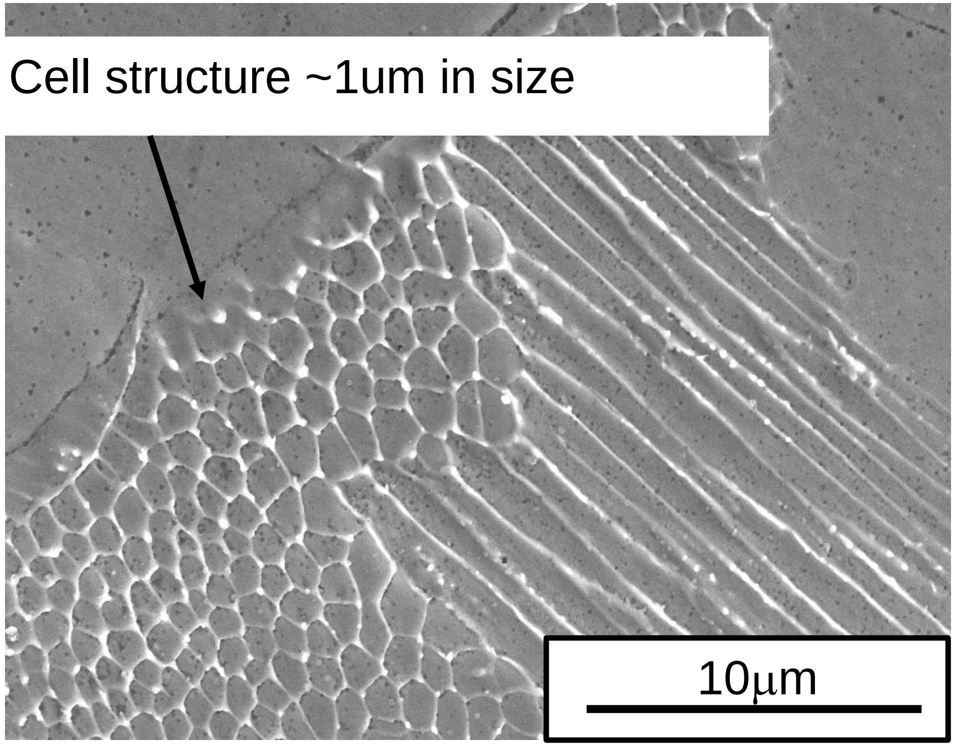
- Q4 Go/No go: Demonstrate compatibility, defined by absence of defects greater than 100 μm and **yield strengths equivalent to cast material at 600-800°C**, of one LPBF austenitic stainless steel. **COMPLETE**

Approach: AM parameter optimization: Design of Experiments + Fast high throughput screening

- Start with known 316L, then develop new high strength AM Austenitic Alloys
- Thrust 4B: Adv. Comp. to predict phase formation and optimize alloy composition
  - Finite element analysis (FEA)
  - Thermodynamic
- Single laser track experiments
  - Fast screening of austenitic alloys
- Characterization
  - Microstructure (Subtask 4A: Adv.Char.)
  - Mechanical properties

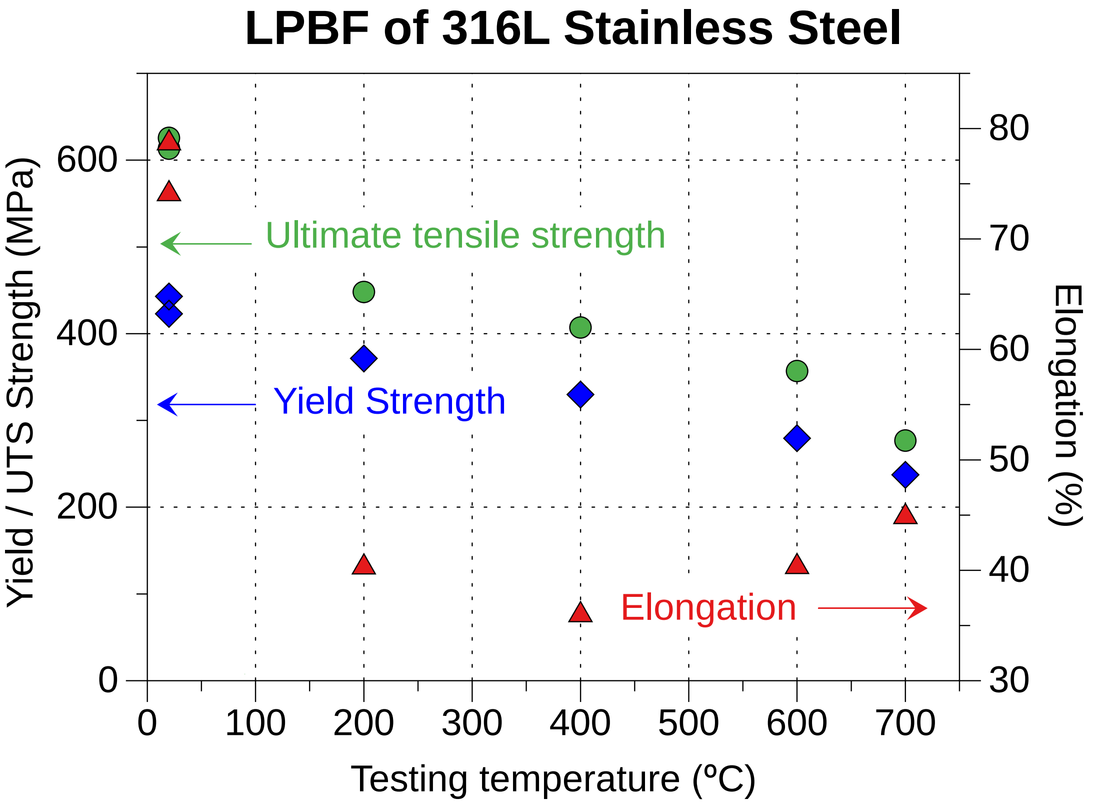


Tech. Accomp.: Specific Microstructure of LPBF 316L Leads To Superior Ductility & Strength At Room Temperature

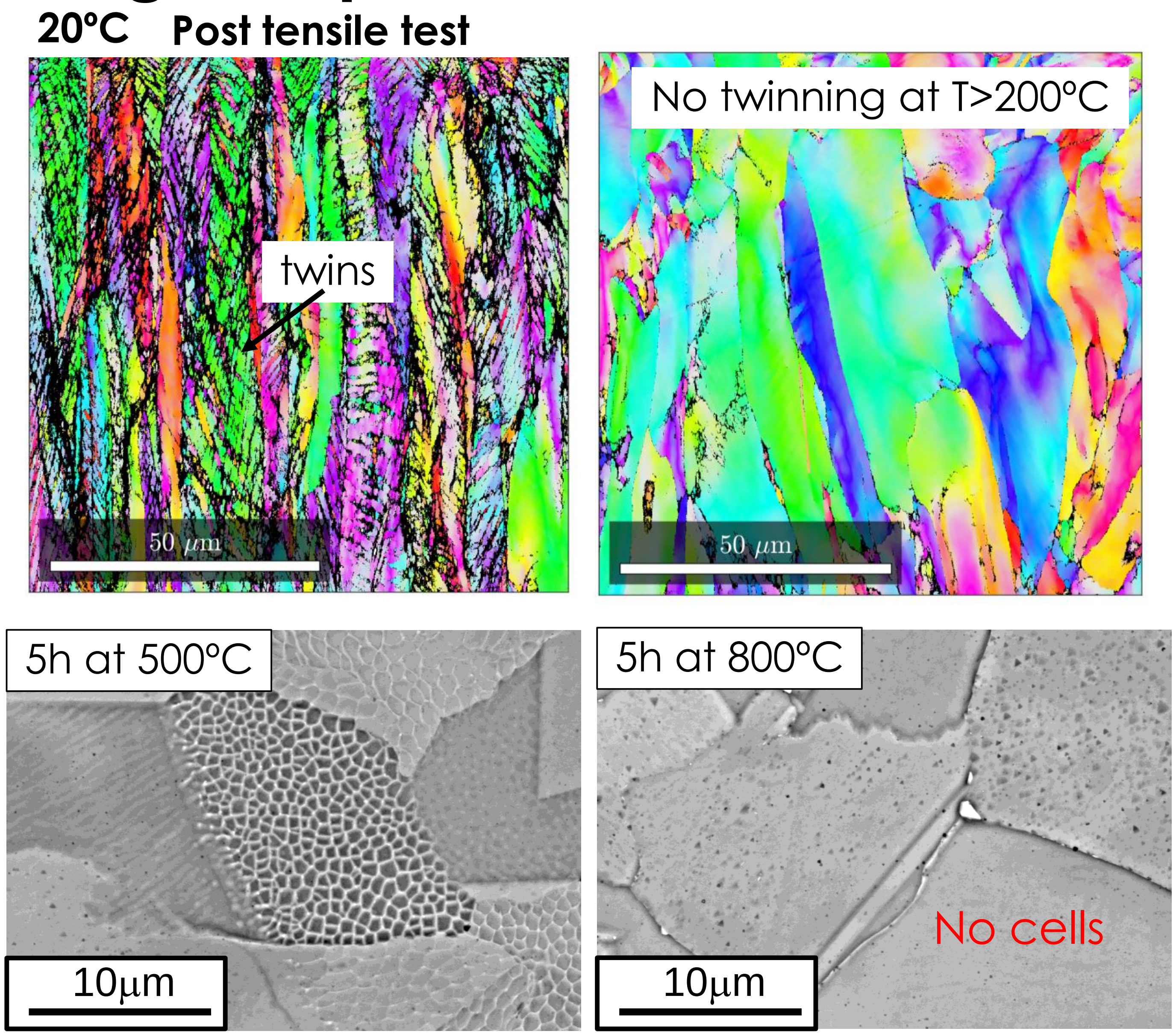


- Cell structure with high dislocation density results in high strength directly related to cell size
- Very few defects + grains slightly elongated along build direction

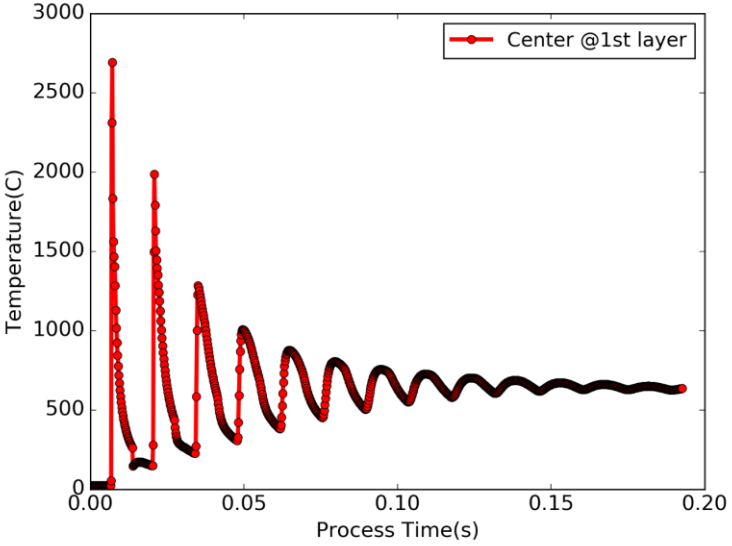
Tech. Accomp.: Progressive Decrease of Yield Strength and UTS with Increasing Testing Temperature



- **Significant decrease of ductility at T>200°C**
- **How can we improve the cellular structure stability?**

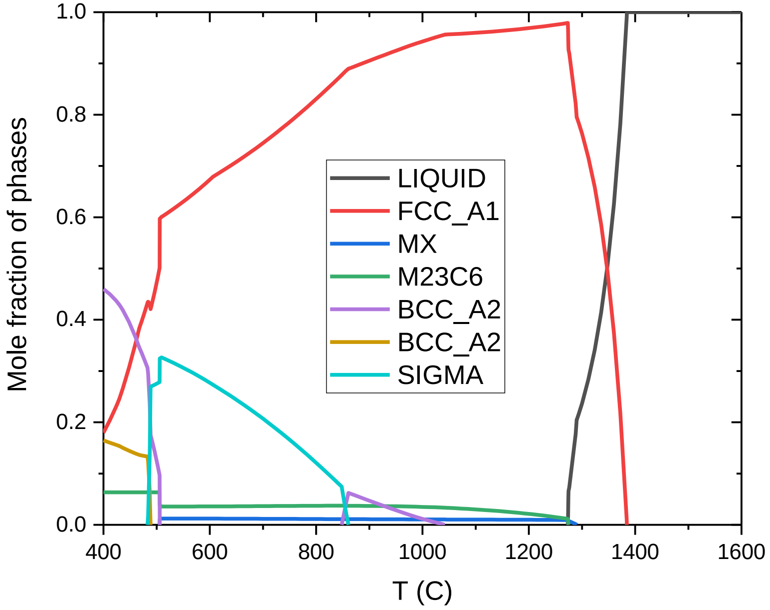


Tech. Accomp.: Activities & a Key Result from Thrust 4B: Advanced Computation: Key tools: FEA & CALPHAD

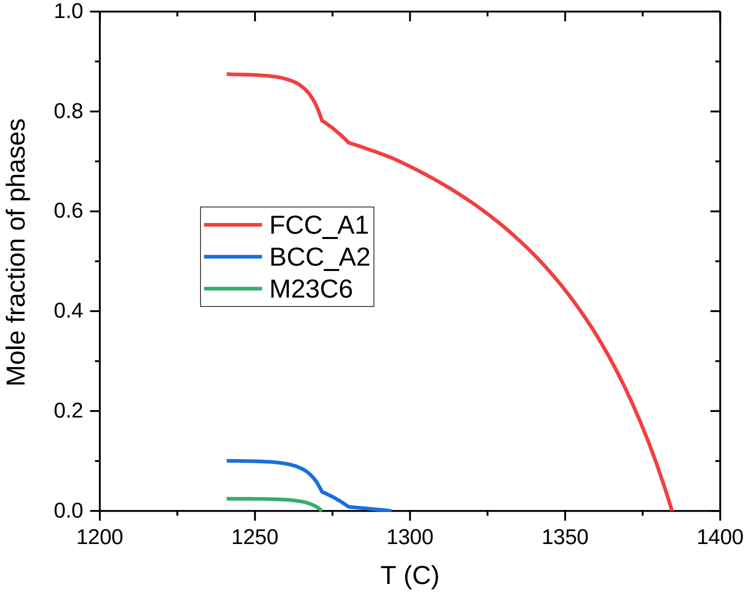


Thermal cycle for both single track and actual build

Equilibrium phases HK30Nb

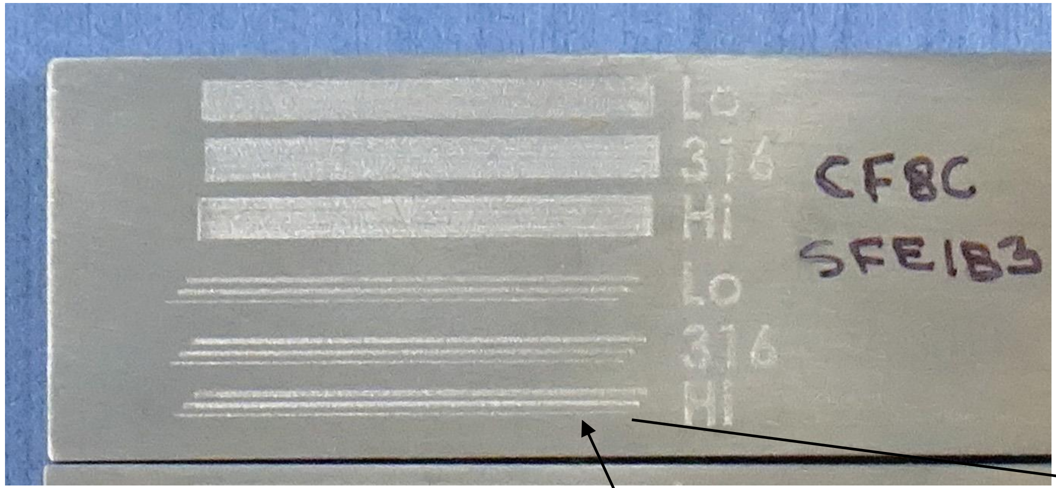


Solidification phases HK30Nb (Scheil)

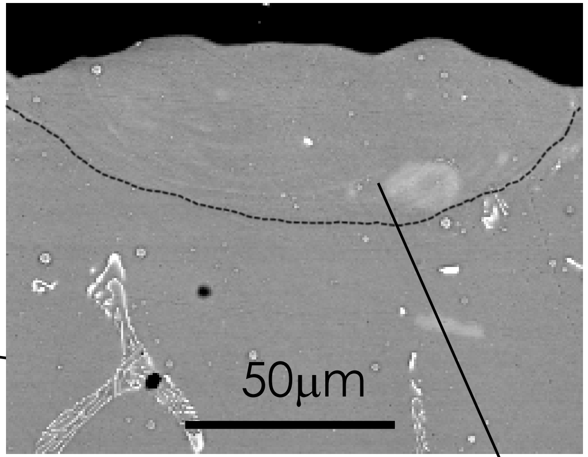


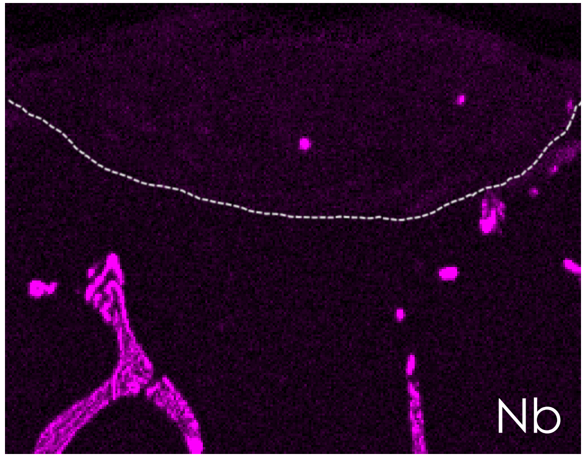
Tech. Accomp.: Single Track Experiments For Fast Screening of new AM Higher Temp. Austenitic Alloys of Varying Compositions

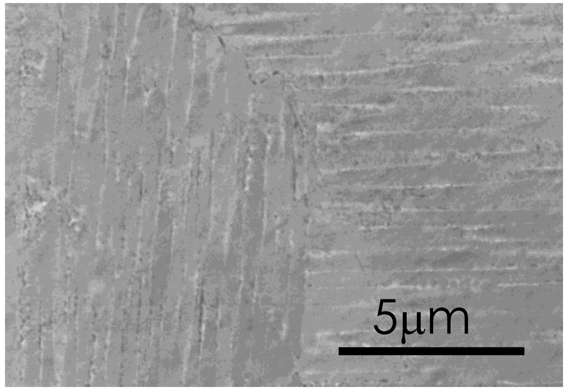
Plates were machined from 7 different cast alloys (HK30Nb, CF8C+, CF8C+W/Cu, etc.) and inserted in Renishaw laser machine



1 to 3 laser tracks, + variation of laser parameters around 316L std parameters



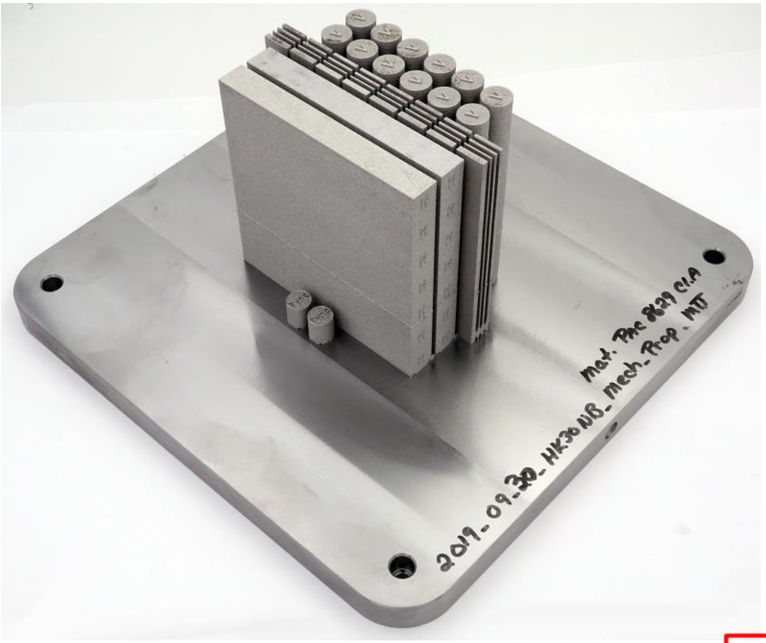


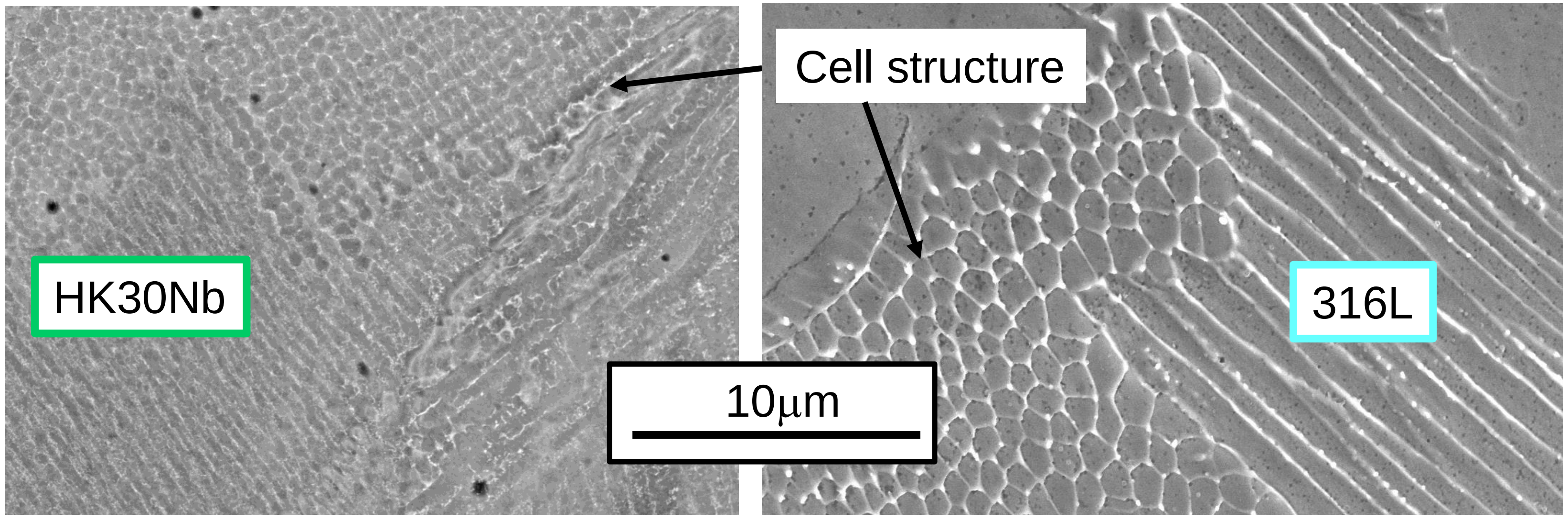


- No cracks observed
- Disappearance of large cast carbides
- Cell structure observed

TEM planned in FY20 to evaluate nano precipitates

Tech Accomp./(Milestone MET): New High-C Alloy, Similar Microstructure to 316L But Much Finer Cellular Structure

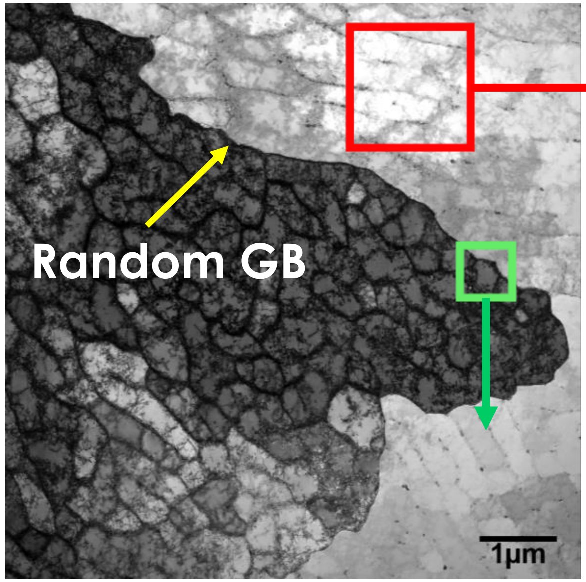


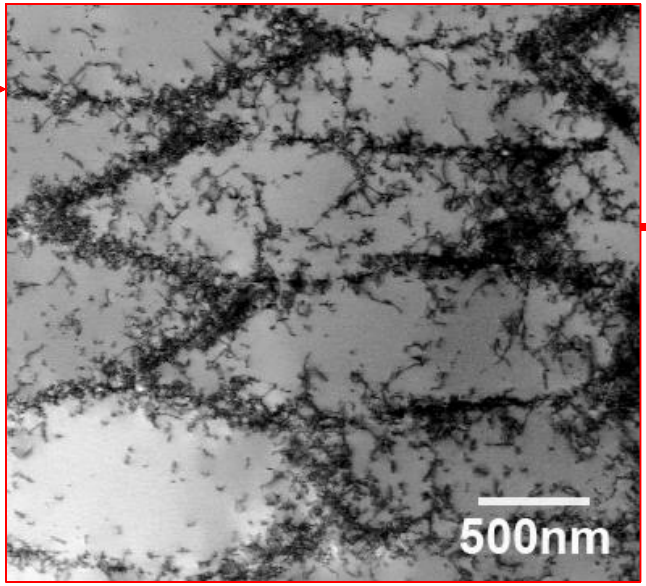


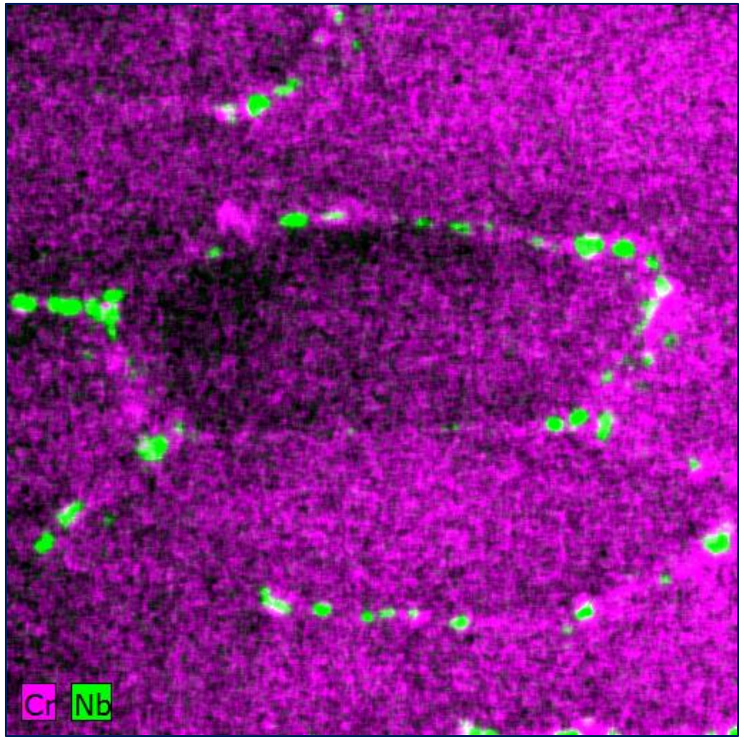
Alloy	Fe	Cr	Ni	Mo	Mn	C	Nb	Si
316L	66.9	16.9	11.9	2.6	1.1	0.008	0	0.43
HK30Nb	Bal.	25	21	0.3	0.2	0.22	1.3	1.1

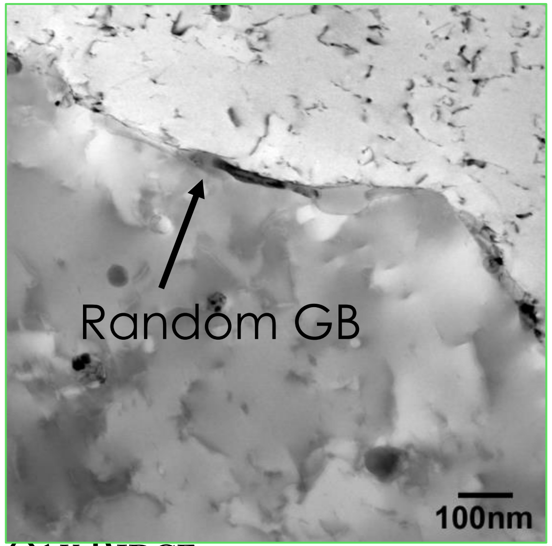
First time HK30Nb has been fabricated by AM!

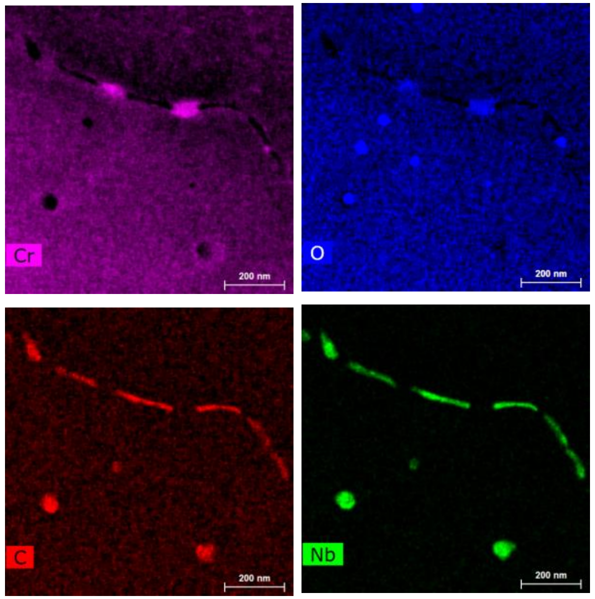
Tech Accomp.: (via Subtask 4A: Adv. Char), Scanning Transmission Electron Microscopy (STEM) confirmed the presence of fine, strengthening NbC precipitates in the dislocation walls of the LPBF HK30Nb cellular structure





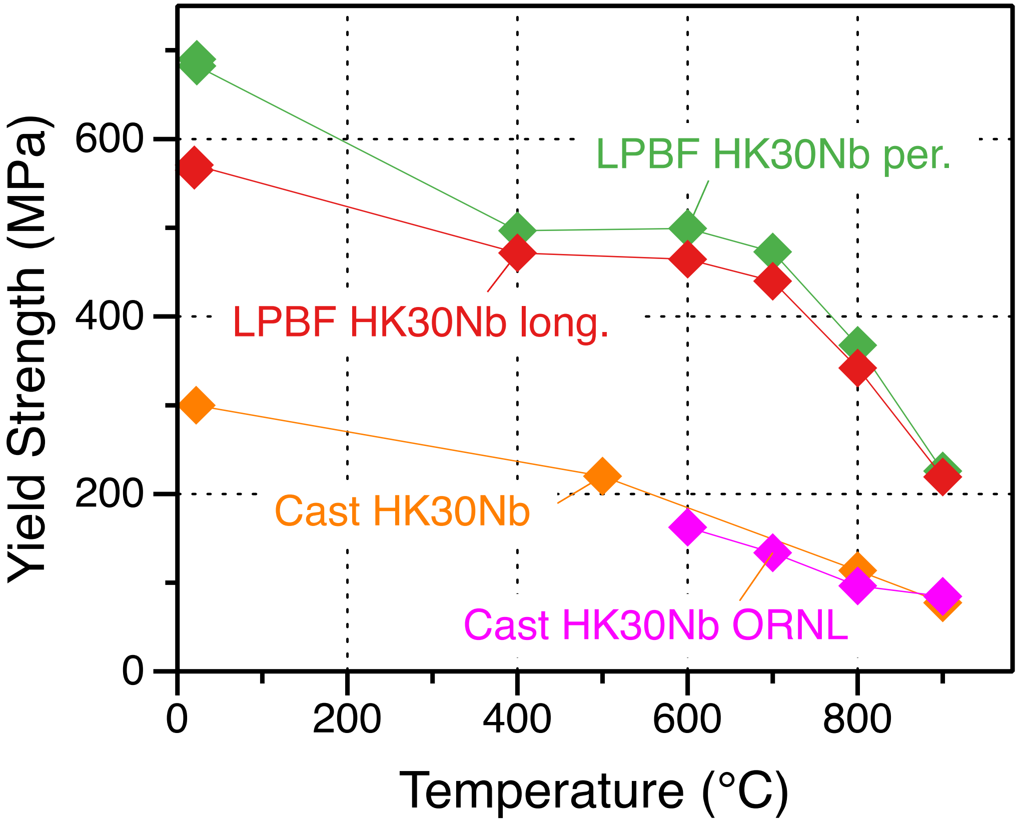


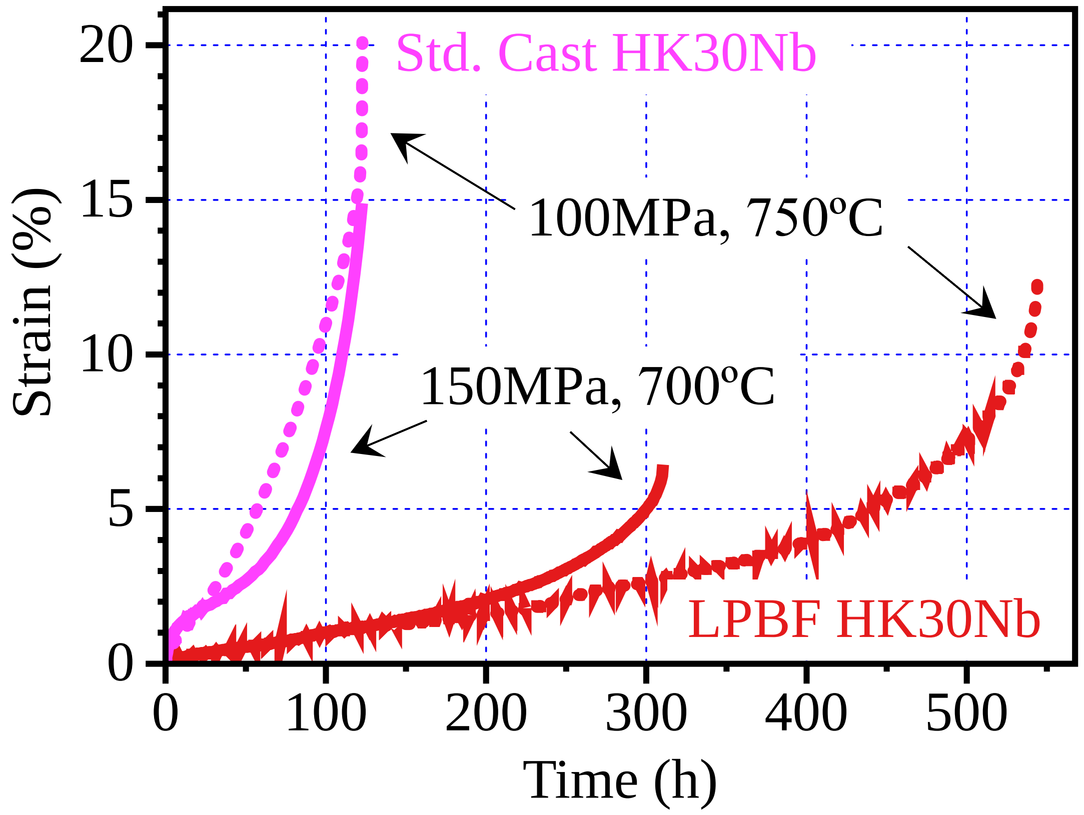




- Cr segregation/precipitates in the walls
- Elongated NbC and Cr-rich oxide at grain boundary

Tech Accomp. (Go/No go): LPBF HK30Nb Exhibits Superior Strength at 20-900°C Compared to Cast HK30Nb





- AM alloy: very high strength at 600-800°C
- Also, very good creep lifetime at 700-750°C

Responses to Previous Year Reviewer's comments

- Project was not reviewed last year

Collaboration and Coordination with Other Institutions

- FY19. Thrust 4B Advanced Computation
  - Thermodynamic & Kinetic Computations
- FY20. Thrust 4A: Advanced Characterization
  - Scanning Transmission Electron Microscopy to understand Carbide Disappearance
- Seeking industrial collaboration

Future Research

- Generate mechanical property data on LPBF HK30Nb steel
  - Creep, oxidation, fatigue, toughness
- Fabrication of Carbonitride strengthened CF8C+ steel by LPBF
  - Custom made, high N powder was purchased
  - Parameters Optimization + Microstructure & properties characterization
  - Better understanding of precipitate/cellular interaction during fabrication, aging and creep testing
- Austenitic alloy design
  - Improve thermal cycle modeling and phase prediction
  - Develop selection method based on single-track experiments

Any proposed future work is subject to change based on funding levels.

Project Summary

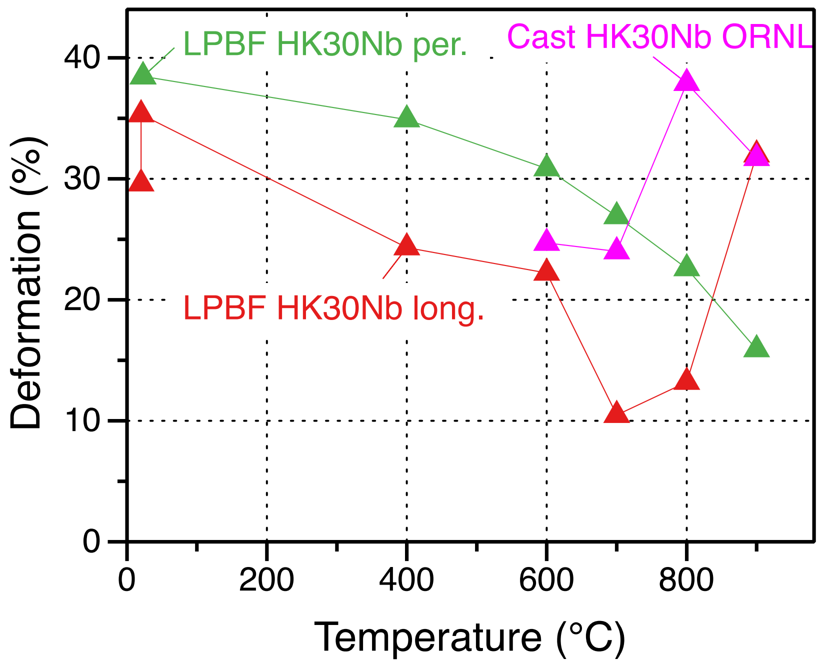
- Successful additively manufactured commercial alloy HK30Nb
  - First time (known) for this alloy to be fabricated by AM.
  - High carbon austenitic steels can be fabricated by LPBF w/no cracking.
  - Very good creep strength due to fine carbides in microstructure.
  - There are likely mechanical properties advantages via AM.
- Design strategy
  - Project leverages an ***Integrated computational materials engineering*** (ICME) framework developed for cast aluminum alloys
  - Improving modeling tools
  - Single track experiments to alleviate the need for powder production
  - Key microstructure very refined compared to cast alloys
  - Dislocations cells offer route to design new alloys

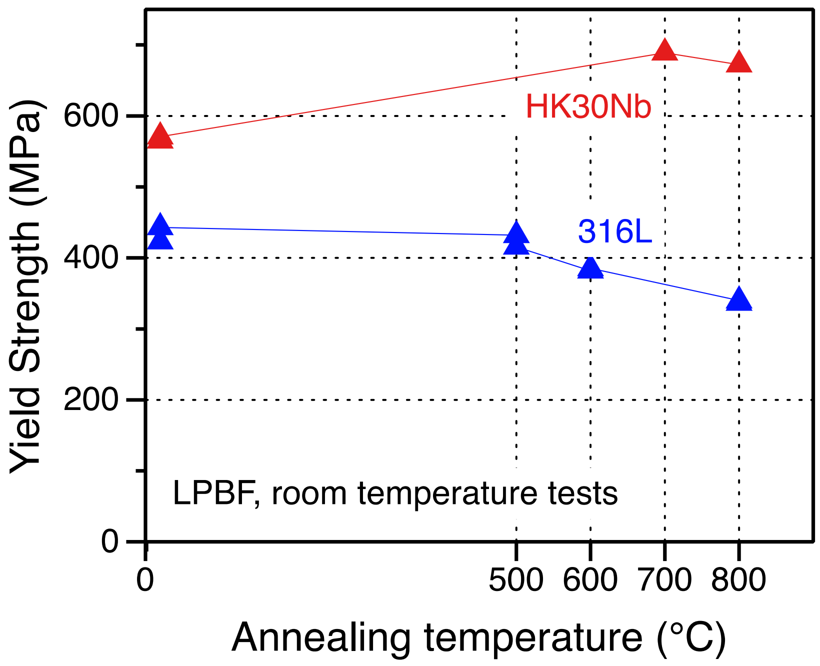
Backup Slides

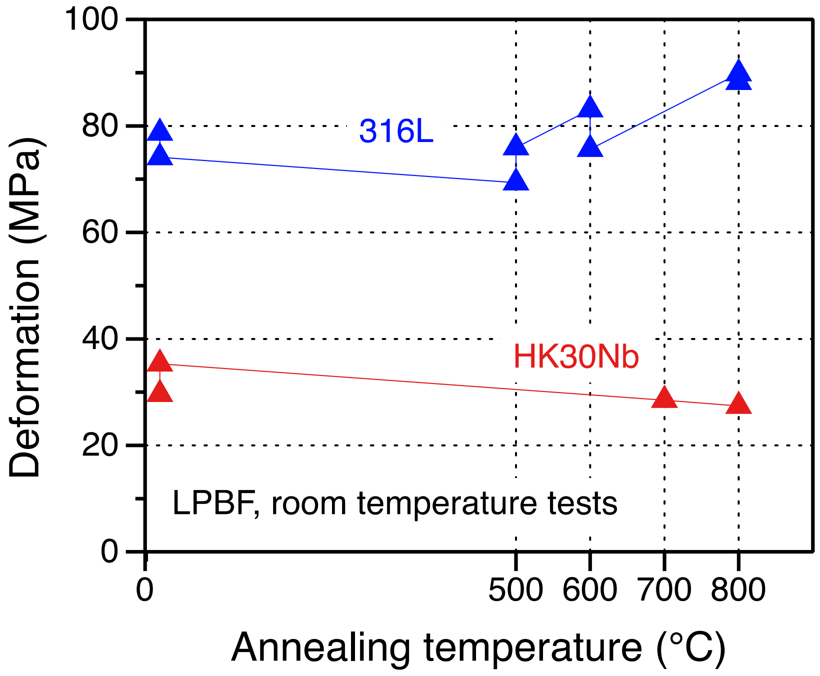
Challenges & Barriers

- Non-equilibrium solidification conditions
  - Thermodynamics are not consistent with alloy solidification due to high solidification rates. Need better predictive tools
  - Need better understanding of cell formation and precipitate interaction mechanisms to locally control and improve the alloy properties
- Reduce time to develop, fabricate and characterize new alloys
  - Powder processing; fabrication for new alloys is very time consuming
  - Need to advance our single-track experiments to accelerate alloy development/selection

Tech. BackUp: Increase of Strength for LPBF HK30Nb after 5h at 700 and 800°C.







- Cellular structure favors precipitate nucleation
- Precipitates stabilize the microstructure/pin dislocations at high temperature